2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Robot Design for High Flow Liquid Pipe Networks

Changrak Choi* and Kamal Youcef-Toumi

Abstract— **In-pipe robots are important for inspection of pipe network that form vital infrastructure of modern society. Nevertheless, most in-pipe robots developed so far are targeted at working inside gas pipes and not suitable for liquid pipes. This paper presents a new approach for designing in-pipe robot to work inside a liquid environment in the presence of high drag forces. Three major subsystems – propulsion, braking, and turning – are described in detail with new concepts and mechanisms that differ from conventional in-pipe robots. Prototypes of each subsystem are designed, built and tested for validation. Resulting is a robot design that navigates efficiently inside liquid pipe network and can be used for practical inspection purposes.**

I. Introduction

In-pipe robots play an important role in the inspection of pipelines. Pipe networks form vital infrastructures that act as a sustaining backbone of today's modern society. Thus, it is highly important that these pipe networks are well inspected to ensure proper working. However, most pipelines are buried deep underground and are not reachable by a human inspector. Deploying a robot inside the pipe network provides an attractive solution for effective inspection [1].

Many in-pipe robots are developed and built for inspection purposes. The research on robots for pipe inspection dates back to late 1980's [2, 3]. A large body of work has been compiled in this area from robotics community since and various in-pipe robots have been built [4]-[16],[21]. Figure 1 shows examples of such in-pipe robots.

Nearly all of the in-pipe robots use wheel as the principle mean of locomotion [17]. This is because wheels provide simple but effective way of satisfying three major functions of in-pipe locomotion – propelling, braking and turning. Propelling and braking of the robot can be done by accelerating and decelerating the wheels. Moreover, differential wheel drive can be used for turning at the junctions to the desired direction.

However, wheel based locomotion becomes highly inefficient in the presence of large drag from the pipe flow. Drag is an important factor to consider in the design of an in-pipe robot, especially when it needs to operate in a high flow pipe [1]. This becomes even more so if the robot is to travel in a liquid medium which has high density (e.g. water pipeline). Surprisingly, previous works on in-pipe robot do not take into account the effect of drag into their design consideration. Hence, what results is a design that may be valid for low flow gas pipes, but not otherwise.

C. Choi and K. Youcef-Toumi are with Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

The authors would like to thank the King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia, for funding the research reported in this paper through the Center for Clean Water and Clean Energy at MIT and KFUPM.

* Corresponding author (e-mail: changrak@ mit.edu).

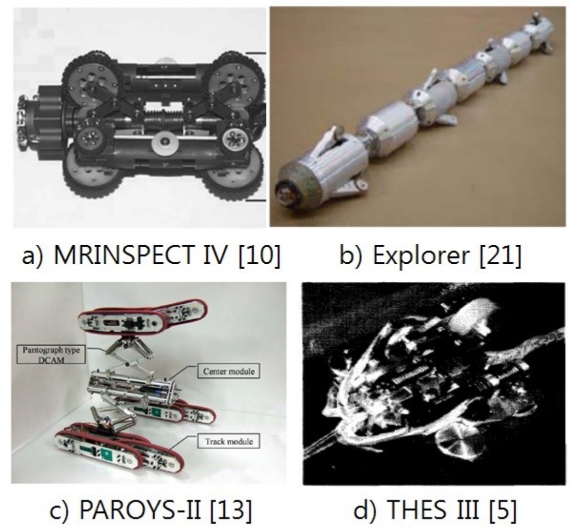

Fig. 1. Most in-pipe robots use wheels for locomotion which is not efficient when working inside a liquid pipe network.

This paper presents new approach for designing robot for liquid pipe network where high drag force is present. Section II addresses the limitations of wheel based locomotion in such circumstances. Section III gives the overview of the robot design approach with Section IV, V, and VI discussing braking, turning and propulsion subsystem of the robot in detail. New concepts and mechanisms for each subsystem are presented in the way that differs from the conventional in-pipe robots. Section VII discusses several related issues and the paper sums up with conclusion in Section VIII.

II. Limitation of Wheel-based Locomotion

Drag plays a significant role and must be considered when designing a robot to work inside a liquid pipe network. This is because drag is proportional to the density of the fluid and liquid has density about three orders of magnitude higher than that of a gas. For example, water has a density of 1000 kg/m^3 whereas density of air is only 1.2 kg/m^3 and such difference directly translates to the difference in the drag.

Drag experienced by the robot inside the pipe consists of two types – pressure drag and friction drag. Pressure drag is caused by the pressure difference between the front and rear part of the robot. It is mainly due to flow separation around the robot that deters rear side pressure value from recovering to the frontal pressure. To decrease the pressure drag, the robot shape needs to be streamlined. Friction drag, on the other hand, is caused by the shear stress acting on the surface of the robot. It is due to viscosity of the fluid and the velocity gradient present on the surface of the robot. To decrease the friction drag, the robot must have small area blockage of the pipe cross-section so that the flow velocity around the robot is not high.

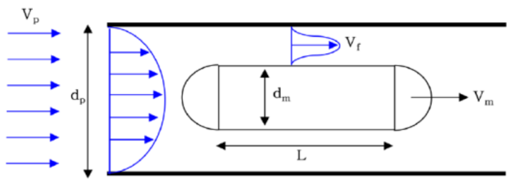

Fig. 2. Robot inside a pipe experiences drag. The total drag acting on the robot is sum of the pressure drag and the friction drag. (Drag = $D_{pressure} + D_{friction}$)

Wheel-based locomotion inherently leads to a robot design that experiences large drag force. To use wheels to navigate, wheels need to be mounted on the robot with necessary transmission and motor connected to them. Moreover, a separate motor is required by each wheel in order to perform differential drive to turn at the junctions. Such requirements make it hard for the robot to be streamlined and also increase the blockage area caused by the robot as evident from Fig. 1. The former increases the pressure drag and the latter friction drag.

High drag force on the wheel-driven robot creates two major problems. First, it becomes hard to keep the traction on the wheel. Keeping traction is the pre-requisite for the wheel based locomotion to work properly [8]. With the high drag acting on the robot, more friction is needed to maintain the traction. This will require the robot to apply high normal force on the wheels, thereby requiring more torque from the motor in driving the wheels.

More problematic is the fact the motor driving the wheel has to act against the drag (flow). The flow speed inside the typical liquid pipe (e.g. water pipelines) is often higher than the speed at which an in-pipe robot has to travel. For example, water pipelines have flow between 1m/s to 2m/s in normal circumstances [1]. A robot performing careful inspection would require to travel at a speed far lower than this. Therefore, motor driving the wheel will need to overcome the torque created by the drag in most circumstances and expend significant energy.

Wheel-based locomotion is not efficient inside a liquid pipe network where drag is significant. It fails to navigate through liquid pipe environment efficiently in terms of energy. This is a serious drawback as in-pipe robots must be able to operate for a long period time in a single run for practical purposes. Therefore, a new design approach must be taken that has efficient means of locomotion for liquid pipe networks.

III. Overview of Robot Design Approach

In-pipe robot design must satisfy certain functional requirements in order to effectively navigate and inspect pipe networks. Table I lists the functional requirements to be satisfied.

The first three functional requirements – braking, turning, and propelling – are directly related to the locomotion of the robot. Figure 3 shows a schematic of a new in-pipe robot design approach that meets these functional, aimed at performing an efficient navigation inside liquid pipe networks.

Three major subsystems – magnetic brake, flexible joint, and propulsion unit – act together to provide speed control, maneuverability, and propulsion capability needed for locomotion. Each subsystem represents a new concept and/or

TABLE I. Functional Requirements

Functional	Description
Speed Control (Braking)	Must be able to slow down and adjust speed in high ambient flow
Maneuverability (Turning)	Must be able to turn at the junctions to a desired direction
Propulsion (Propelling)	Desirable to propel forward when ambient flow become stagnant
Energy Efficient	Highly desirable for long operational hours
Stability	Desirable to travel stably along the centerline of the pipe
Untethered	Must have all the components on-board

mechanism that differ from the ones employed by the

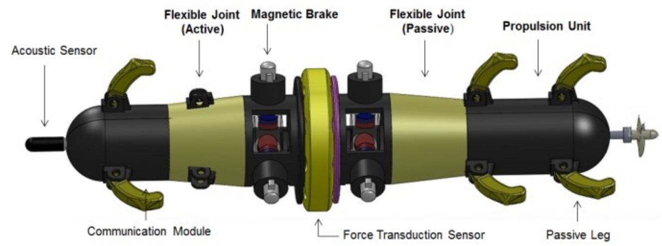

Fig. 3. A new in-pipe robot design approach that performs locomotion efficiently inside a liquid pipe network is presented.

conventional wheel-based robot. Following three sections present the subsystems in detail.

IV. Magnetic Brake for Speed Control

In-pipe robot inside a high-speed liquid pipe is naturally propelled by the drag and travels quickly, almost at the speed of the flow [1]. What then becomes really important is having a braking mechanism that can slow down and adjust the speed of the robot in a high ambient flow. Ability to control the robot speed is a must to ensure a proper inspection of the pipelines.

This section describes a novel magnetic brake mechanism that differs from conventionally used linkage and has more energy efficient performance. More elaborate detail and in-depth analysis of the mechanism is given in the paper by C. Choi and el. [18],[20].

A. Design Approach

Using friction between the robot's leg and the pipe wall is a natural and effective way of creating the braking force needed. For an in-pipe robot to travel stably in a high ambient flow, it must have legs extending to the wall to support itself. Here, by applying a normal force on the leg against the pipe wall, a friction can be created. Moreover, by controlling the magnitude of this normal force, friction can act as a brake to control the speed of the robot.

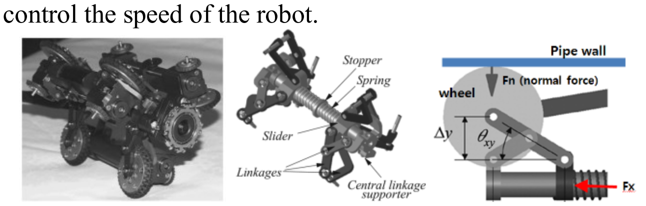

Fig. 4. Previously developed in-pipe robots use linkage mechanism to create normal force which is not energy efficient [8].

Previously designed in-pipe robots use linkage mechanism to provide the normal force on the legs [4]-[16]. Figure 4 shows typical linkage mechanism used. Although their purpose is to create required traction on the wheels, same linkage mechanism can be used to create friction to act as a brake.

However, using linkage to create normal force is not energy efficient. A simple analysis shows that to create large normal force (F_n), a large force (F_x) in proportion is needed from the actuator that drives the linkage. Producing a large braking force is unavoidable when the in-pipe robot needs to travel slowly in a high ambient liquid flow. This leads to the linkage mechanism expending a significant energy in its operation.

A new design approach is needed that could create a large normal force while having a small torque requirement on the actuator.

B. Magnetic Brake Mechanism

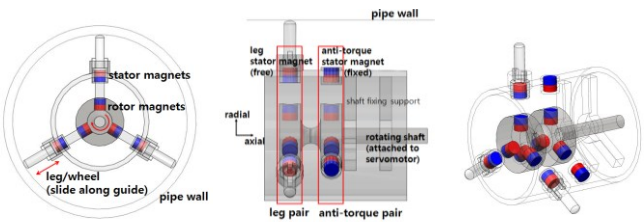

Fig. 5. Magnetic brake mechanism uses magnetic forces between the rotor and stator magnets to create normal force in an energy efficient way.

Figure 5 shows the magnetic brake mechanism designed for the purpose discussed above. The mechanism uses permanent magnets and magnetic forces to create normal force. It consists of rotor and stator magnets. Rotor magnet is attached to a disk that is rotated by a servomotor. Stator magnet is attached to the end of each leg.

Stator and rotor magnets form two pairs – leg and anti-torque pair – as shown in the middle diagram of Fig. 5. Leg and anti-torque pair are exactly identical in their configuration but differs only by the stator magnet's polarity and location. The stator magnets of the anti-torque pair have their poles reversed from that of the leg pair and are attached to the circumference of the robot's body rather than at the end of legs.

C. Generation of Controllable Friction / Torque Cancellation

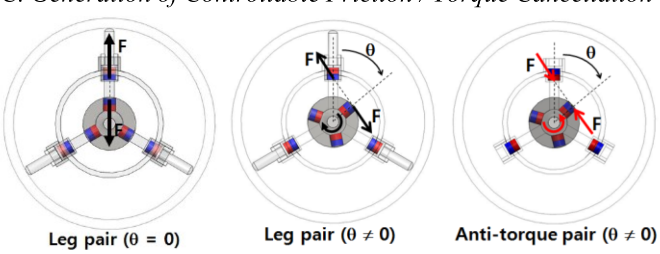

Fig. 6. Leg pair produces a controllable normal force while the anti-torque pair cancels out the torque produced by the leg pair. This enables generation of controllable friction with zero torque requirements.

Leg pair of the magnetic brake mechanism works to produce the controllable normal force on the legs. Due to the like poles facing each other, a repulsion force is created between the rotor and stator magnets. This repulsion force pushes the leg against the wall which generates the normal force. Now, as the rotor magnet rotates, that is as the angle θ increases, the distance between the rotor and stator magnet is increased. The increase in distance reduces the magnetic repulsion acting in between and leads to smaller normal force. Therefore, by controlling the rotation angle θ by a servomotor, the leg pair is able to produce a controllable friction on the legs. Graph shown in Fig. 7 shows a simulation of this in effect.

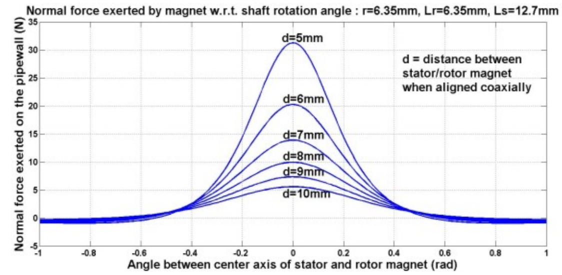

Fig. 7. Magnetic brake is able to create a controllable friction on the leg by rotating the rotor magnet to a desired angle using a servomotor.

Anti-torque pair of the magnetic brake acts to cancel out the torque required by the servomotor in operating the mechanism. The repulsion force created by the leg pair exerts a torque on the rotor magnet disk which needs to be overcome by the servo when driving the system. However, the anti-torque pair has poles reversed and produces torque on the disk that is equal in magnitude but opposite in direction. Therefore, when anti-torque pair is put together with the leg pair, the resulting torque on the disk becomes theoretically zero. This means that the servomotor would only need a very small torque to operate the mechanism while producing a large range of normal force. Graph below in Fig. 8 demonstrates the torque cancellation.

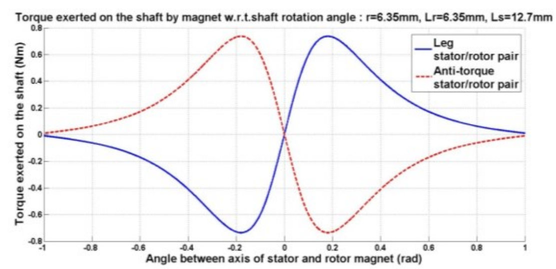

Fig. 8. Magnetic brake produces controllable friction with zero torque required from the driving servomotor, making it energy efficient.

D. Design Parameters and Force Analysis

TABLE II. DESIGN PARAMETERS

Symbol	Description
r	radius of rotor/stator magnets
l	length of the rotor/stator magnet
B_0	strength (remanence) of magnet
d	distance between rotor and stator magnet when aligned coaxially

Table II shows important design parameters of the magnetic brake mechanism. All of these parameters directly affect the range of the normal force produced by the mechanism. To find how these parameters affect the normal force, a quantitative analysis of the magnetic forces is required.

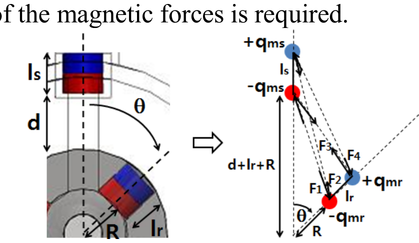

Fig. 9. Quantitative analysis of the normal force produced by the mechanism can be performed by modeling a magnet as magnetic charges.

Magnetic forces acting in the mechanism can be calculated by modeling the magnets as magnetic charges. Then by summing up the forces between the magnetic charges, the resulting normal force produced can be derived. A detail of the calculation is omitted here, but the analysis gives the following expression that relates the maximum normal force produced to the design parameters. This provides a scaling law that could act as guidance in designing the magnetic brake to produce the desired range of normal force needed.

$$F_n\Big|_{\max} = \frac{\pi B_0^{\,2} r^4 l^2}{\mu_0 d^2 (d+2l)^2} \tag{1}$$

E. Prototype and Experiments

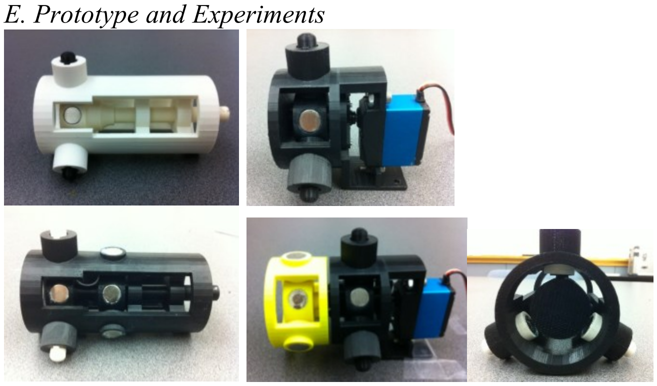

Fig. 10. Two prototypes of magnetic brake are built. Prototypes verify the ability of the mechanism to produce controllable normal force while consuming very little energy.

Two prototypes of the magnetic brake are built to verify the working of the mechanism. Prototype I only has a leg pair whereas prototype II has both the leg and anti-torque pair. This is done on purpose to test for the effectiveness of the anti-torque pair in cancelling out the torque.

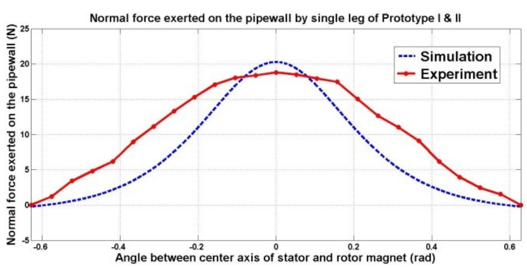

Fig. 11. Normal force measurement shows that magnetic brake produces controllable normal force which agrees well with the simulation.

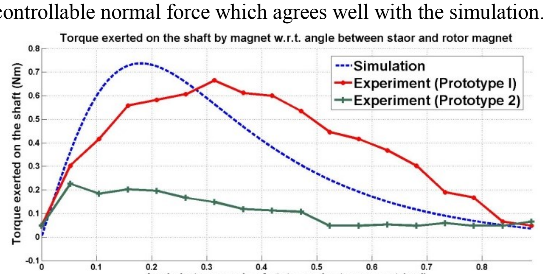

Fig. 12. Torque measurement shows that the anti-torque pair is effective in canceling out the required torque and makes the mechanism energy efficient.

Experiments were performed on the two prototypes to measure the normal force produced and the torque required in the process. Figure 11 shows the normal force curve as a function of the rotation angle. The leg pair produces normal force which varies with the angle θ as expected. Figure 12 shows the torque required by the servomotor in operating the mechanism to produce the normal force. Prototype II, with the added anti-torque pair, clearly has the required torque significantly reduced from that of the prototype I. Hence, the magnetic brake, with leg and anti-torque pair working together, is able to produce a large range of normal with very small torque required and consume little energy.

V. Flexible Joint for Maneuverability

A. Motivation

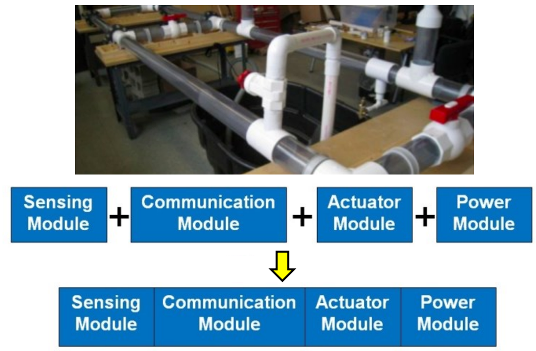

Fig. 13. Junctions in the pipe networks restrict the length of the robot. Rigid robot may become too lengthy to travel around the bends.

Pipe network has many junctions that the in-pipe robot needs to travel through. Such bends (e.g. Y or T junctions) restrict the maximum length that a rigid robot can have. From a simple calculation, it can be shown that an in-pipe robot (having a diameter of 60mm) cannot be longer that 170mm when traveling inside 100mm diameter pipe bends.

This is a small space considering the different modules that needs to be on-board to perform required task. When different modules are put together, the in-pipe robot can easily become too lengthy to negotiate the turns.

B. Concept of Flexible Joint

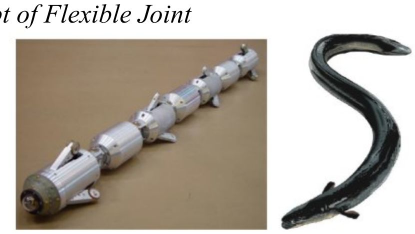

Fig. 14. Rigid joints create discontinuity in the robot's body that greatly increases the drag coefficient. Nature, on the other hand, has evolved to have a continuous shaped body for its swimming creatures.

Joints can be used to enable an in-pipe robot to negotiate the junctions even if it becomes long. However, connecting the modules with rigid joints creates two problems. First, the discontinuity introduced by the rigid joint significantly increases the drag acting on the robot. Moreover, it is not easy to actuate the joint and have moving parts that are sealed from pressurized liquid inside the pipe.

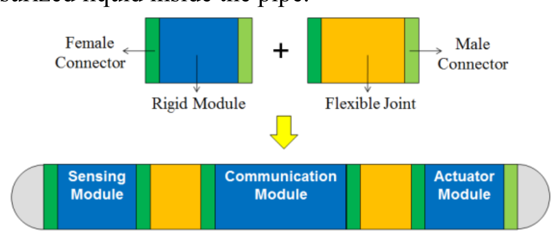

Fig. 15. Connecting rigid modules using flexible joints enables the robot to navigate through bends while maintaining streamlined body.

A flexible joint is developed that has functionality of the rigid joint while overcoming its shortcomings. Figure 15 shows the concept. By connecting different modules with flexible joints, the overall robot can bend like an eel shown in Fig. 14. This helps the robot to turn around the junctions at the same time maintain the streamlined body for drag reduction. Furthermore, by having the flexible joint actuated, the in-pipe robot can have maneuverability to turn at the junctions to the desired direction.

C. Manufacturing Process

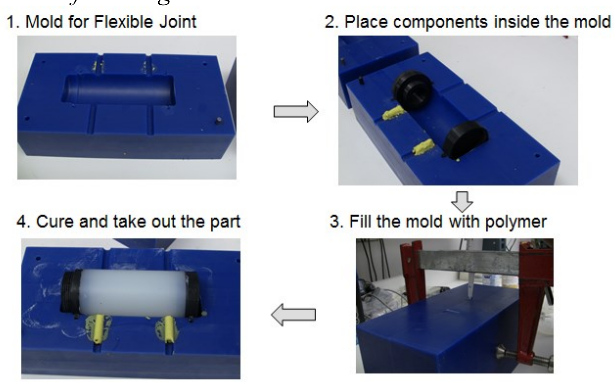

Fig. 16. Flexible joints can easily be manufactured following the procedures shown in the diagram above.

Flexible joint is made following the steps described in the Fig. 16. This manufacturing process is adapted from the procedure for making a flexible fish robot developed by Pablo and el. [19].

The first step is to create a mold that has the shape and length of the flexible joint to be made. The mold in Fig. 16 is made by CNC machining a block of machinable wax. Once mold is made, place the end connectors that will be needed to connect the flexible joint to the rigid modules. At this stage, one can also insert electronics that one wish to embed inside the flexible joint.

Soft polymer is inserted into the closed mold which gives the joint its flexibility. Different type of polymer can be chosen depending on the degree of stiffness and flexibility that is required. After filling the mold with soft polymer, let it cure for a few hours and the flexible joint is ready to be used.

D. Prototype

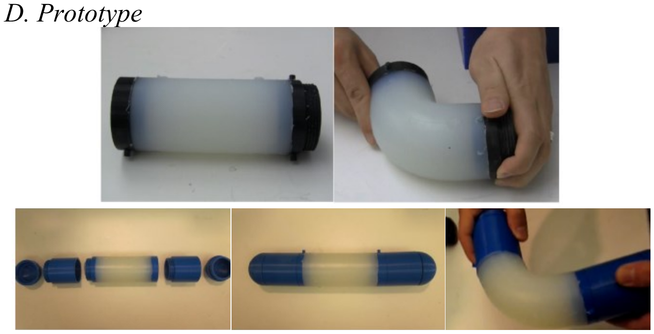

Fig. 17. Flexible joint gives flexibility to the in-pipe robot to bend over 90 degrees which corresponds to the maximum bend inside a pipe network.

Several prototypes of flexible joints are built as a proof of the concept. Top diagram in the Fig. 17 shows a single flexible joint made and demonstrates its ability to bend over 90°. The bottom diagram is a demonstration of connecting different modules with flexible joint as proposed in Fig. 15. Flexible joint enables the robot to bend over the turns while having continuous streamlined shape desirable for reducing the drag.

VI. Propulsion Subsystem

Robot is naturally propelled by the high speed ambient flow inside liquid pipe networks. Nevertheless, there is a need for a propulsion unit for a rare case when the pipe flow becomes stagnant in presence of stopped usage.

A. Different Type of Propulsion System

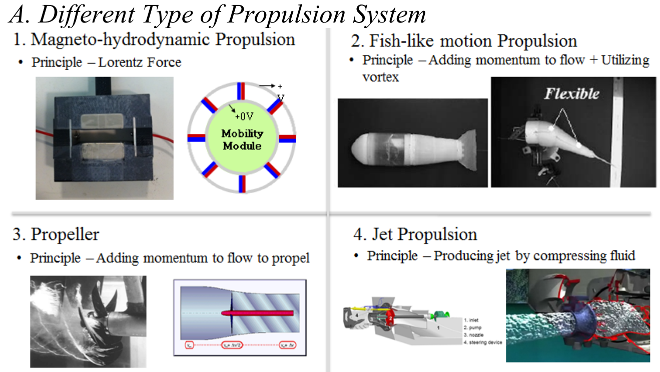

Fig. 18. Various propulsion types exist, each with different working principle that can be used to propel a robot inside liquid pipe networks.

Various propulsion types exist that can be used to propel the robot inside a liquid pipe. Figure 18 shows several propulsion units that can be considered, each with different working principles.

Jet and propeller based propulsions are most suitable for an in-pipe robot traveling inside a liquid pipe. Although the detail of analysis is omitted, propeller produces largest thrust for a given power and has highest efficiency. Jet propulsion, on the other hand, is less efficient compared to propeller but can have greater maneuverability by vectoring the jet exit.

TABLE III. Comparison of Propulsion Systems

Propulsion Type	Advantages	Disadvantages
1. MHD	- No moving part - Silent (does not add noise to the on-board sensors)	- Very small thrust - Bubbles are generated - Magnetic field may interfere with electronics
2. Fish-like motion	- Continuous shape (low drag coefficient) - No issue of sealing under high pressurized flow	- Thrust is small and uneven due to oscillation - Propulsion system requires certain length
3. Propeller	- Large thrust can be produced - Efficiency is high - Low cost commercial parts are readily available	- Creates noise - Propeller can be damaged when hit on the wall of the pipe
4. Jet Propulsion	- Directional propulsion is possible by jet vectoring - Produce sufficient thrust	- Have lower efficiency compared to propeller

B. Prototype (Propeller based Propulsion)

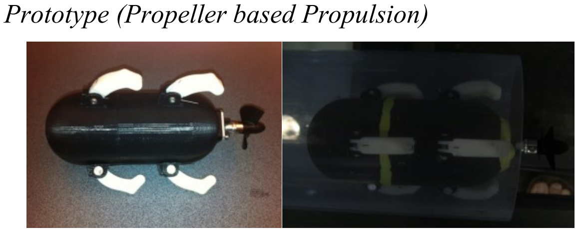

Fig. 19. Propulsion using propeller provides large thrust with high efficiency.

Prototype of propeller based propulsion is built and tested. Experiments show that the robot can travel up to 0.2 m/s inside the water pipe when the flow is stagnant.

VII. Discussion and Future Work

Three major subsystems – magnetic brake, flexible joint and propulsion unit – are presented and prototypes built as a proof of concept for validation. They provide a new design approach to perform locomotion for in-pipe robot traveling inside high flow liquid pipes.

More work certainly needs to be done to optimize the proposed concepts to improve their performance. For example, an analysis can be performed on the flexible joint to relate the design parameters such as length, shape and stiffness to the dynamic response of the joint when subject to external forces. This analysis can be coupled with the design of an actuated flexible joint to find out which method of actuation is most effective.

The concepts and mechanisms presented can also be applicable to other systems and not necessarily confined to the in-pipe robot inside liquid pipe networks. For example, magnetic brake which generates controllable normal force in an energy efficient way can also be used to provide needed traction on the wheels of gas-pipe robots. Flexible joints can also be used as a component inside a robot that needs to have certain parts highly deformable.

VIII. Conclusion

A new design approach for an in-pipe robot for high flow liquid pipe networks has been presented. The new design takes into consideration the drag, which has not been properly addressed by previous in-pipe robot designs despite its importance. As a consequence, the proposed robot design deviates and differs greatly from the conventional wheel based design.

Three major subsystems – magnetic brake, flexible joint, and propulsion unit – are presented and discussed in detail with prototype shown as a proof of the concept. Each subsystem represents a new concept and/or mechanism and they act together to provide speed control, maneuverability, and propulsion capability needed for locomotion.

Resulting is a robot design that overcomes the limitations of the wheeled in-pipe robot and navigates efficiently inside liquid pipe networks. This design can readily be applied to in-pipe robots for practical inspection purposes and increase their performance.

Acknowledgment

A special word of thanks is given to Marie-Fleur Sacreste for the initial work on the flexible joint, especially in manufacturing the mold. Authors would also like to thank Dimitris Chatzigeorgiou for providing CAD files of the passive module upon which the propulsion unit has been built.

References

[1] D. Chatzigeorgiou, K. Youcef-Toumi, A. Khalifa, and R. Ben-Mansour, "Analysis and Design of an In-Pipe System for Water Leak Detection, " in *ASME International Design Engineering Technical Conferences & Design Automation Conference*, 2011.

[2] T. Okada and T. Kanade, "A Three-Wheeled Self-Adjusting Vehicle in a Pipe, FERRET-1", in *International Journal of Robotics Research*, vol. 6, no. 4, Dec. 1987.

[3] T. Okada, "MOGRER: A Vehicle Study and Realization for In-Pipe Inspection Tasks", in *IEEE Journal of Robotics and Automation*, vol. 3, issue 6, Dec. 1987.

[4] K. Suzumori, T. Miyagawa, M. Kimura, and Y. Hasegawa, "Micro Inspection Robot for 1-in Pipes," in *IEEE/ASME Transaction on Mechatronics*, vol. 4, no. 3, 1999.

[5] S. Hirose, H. Ohno, T. Mitsui, and K. Suyama, "Design of In-Pipe Inspection Vehicles for ϕ25, ϕ50, ϕ150 Pipes," in *IEEE International Conference on Robotics and Automation*, May, 1999.

[6] M. Muramatsu, N. Namiki, R. Koyama, and Y. Suga, "Autonomous Mobile Robot in Pipe for Piping Operations," in *International Conference on Intelligent Robots and Systems*, 2000.

[7] M. Komori and K. Suyama, "Inspection robots for gas pipelines of Tokyo Gas," in *Advanced Robotics*, Vol. 15, No. 3, 2001, pp. 365– 370.

[8] H.R. Choi and S.M. Ryew, "Robotic System with Active Steering Capability for Internal Inspection of Urban Gas Pipelines," in *Mechatronics*, 12, 2002, pp.713-736.

[9] C. Jun, Z. Deng, and S.Y. Jiang, "Study of Locomotion Control Characteristics for Six-Wheel Driven In-Pipe Robot," in *IEEE International Conference on Robotics and Automation*, Aug. 2004.

[10] S.G. Roh and H.R. Choi, "Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipeline," in *IEEE Transactions on Robotics*, vol. 21, no. 1, Feb. 2005.

[11] Y.S. Kwon, H. Lim, E.J. Jung, B.Y. Yi, "Design and Motion Planning of a Two-Moduled Indoor Pipeline Inspection Robot," in *IEEE International Conference on Robotics and Automation*, May 2008.

[12] T. Oya and T. Okada, "Development of a Steerable, Wheel-type In-pipe Robot and its Path Planning," in *Advanced Robotics*, vol. 19, no. 6, 2005, pp. 635-650.

[13] J. Park, T. Kim, and H. Yang, "Development of an actively adaptable in-pipe robot," in *IEEE International Conference on Robotics and Automation*, Apr. 2009.

[14] Y. Zhang and G. Yan, "In-pipe inspection robot with active pipe-diameter adaptability and automatic tractive force adjusting," in *Mechanism and Machine Theory*, vol. 42, no. 12, pp. 1618-1631.

[15] M.M. Moghaddam1 and A. Hadi, "Control and Guidance of a Pipe-Inspection Crawler (PIC)," in *International Symposium on Automation and Robotics in Construction,* Sep. 2005.

[16] S. Fujiwara, R. Kanehara, T. Okada, and T. Sanemori, "An Articulated Multi-Vehicle Robot for Inspection and Testing of Pipeline Interiors," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, July, 1993.

[17] J.M. Tur, W. Garthwaite, "Robotic Devices for Water Main In-Pipe Inspection: A Survey," in *Journal of Field Robotics*, 27(4), 2010, pp.491-508.

[18] C. Choi, D. Chatzigeorgiou, R. Ben-Mansour, and K. Youcef-Toumi, "Design and Anaylsis of Novel Friction Controlling Mechanism with Minimal Energy for In-Pipe Robot Applications," in *IEEE International Conference on Robotics and Automation*, May 2012.

[19] P. Alvarado, K. Youcef-Toumi, "Design of Machines with Compliant Bodies for Biomimetic Locomotion in Liquid Environments," in *Journal of Dynamic Sytems, Measurement, and Control*, 2006.

[20] C. Choi, "Robot Design for Leak Detection in Water-Pipe Systems," MS Thesis, MIT, 2012.

[21] H. Schempf, E. Mutschler, A. Gavaert, G. Skoptsov, and W. Crowley, "Visual and Nondestructive Evaluation Inspection of Live Gas Mains Using the Explorer™ Family of Pipe Robots," *Journal of Field Robotics*, Vol.27, Issue 3, Mar. 2010.